Electromagnetic observations of neutron stars

Cole Miller

University of Maryland

Plan of Talk

- Mass measurements from radio observations
- Moment of inertia?
- Radius measurements from X-ray observations
- Future prospects

Will give caveats as appropriate
And Jocelyn will handle GW obs

Summary Before Details

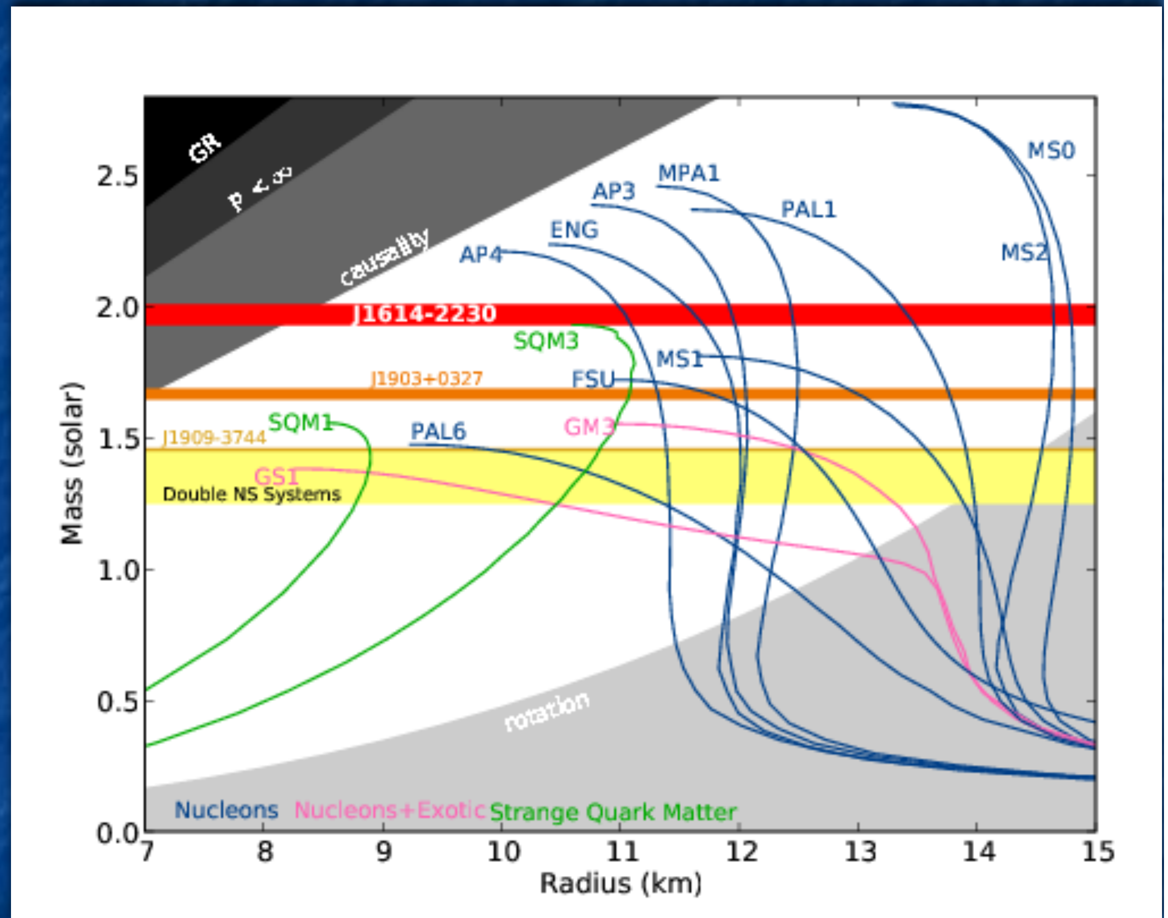
- Radio measurements of masses of NS in binaries yield the most robust constraints
- Radius measurements are constraining but, to quote Mad-Eye Moody, "Constant vigilance!”
- Other measurements (moment of inertia) might be possible, but tougher than thought

Using Measurements

- It is still common that papers on EOS constraints use hard observational cuts, e.g., M_{max}>1.93 M_{sun}; M_{max} above that is fine, below is ruled out
- Please don't do that ☺
- Should use whole distributions; otherwise, get misleading or imprecise results
  See Miller, Chirenti, Lamb 2020 and Alvarez-Castillo+ 2016

NS masses

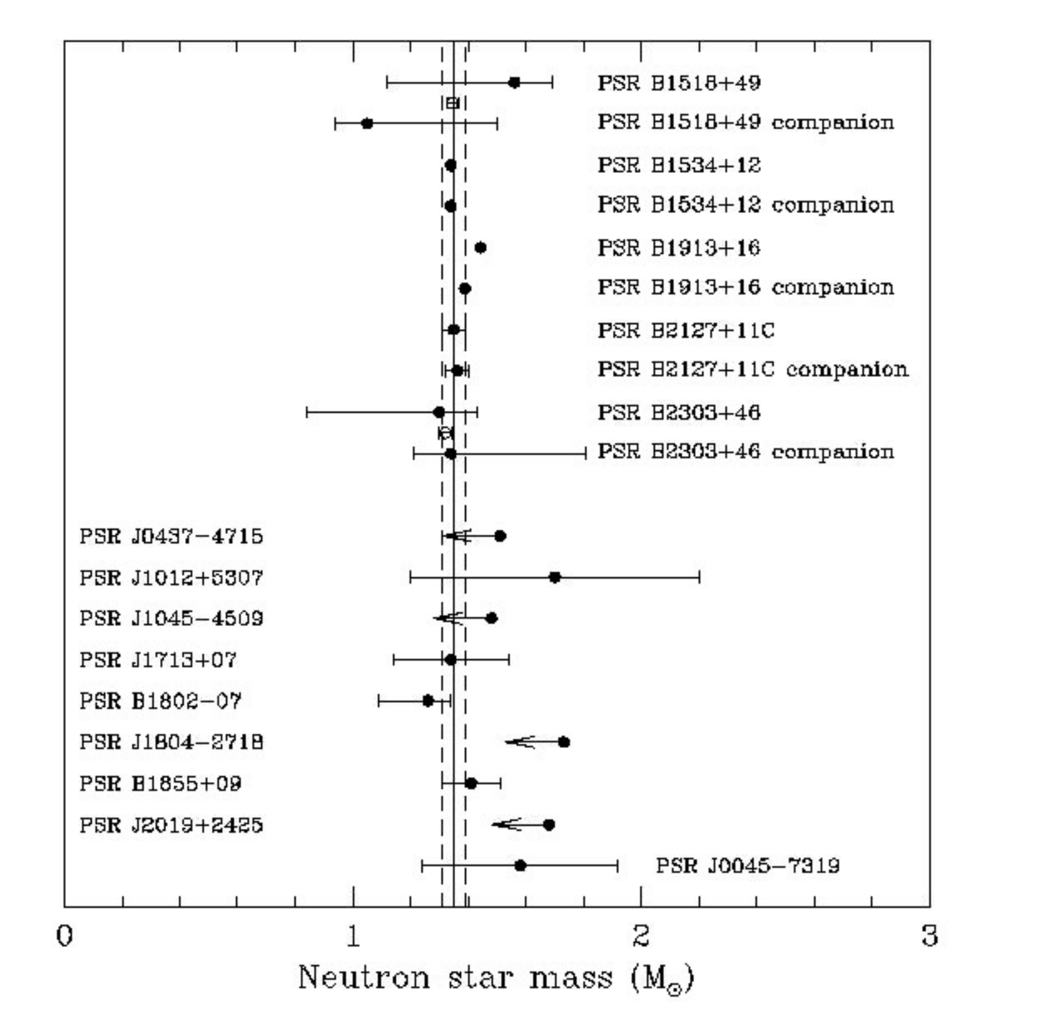
- A given equation of state (EOS) P(ε) (P is pressure, ε is total mass-energy density) predicts M(R)
  Assume equilibrium
- Also predicts maximum mass
- Viable EOS must accommodate largest measured mass



Demorest et al. 2010

Double NS Masses

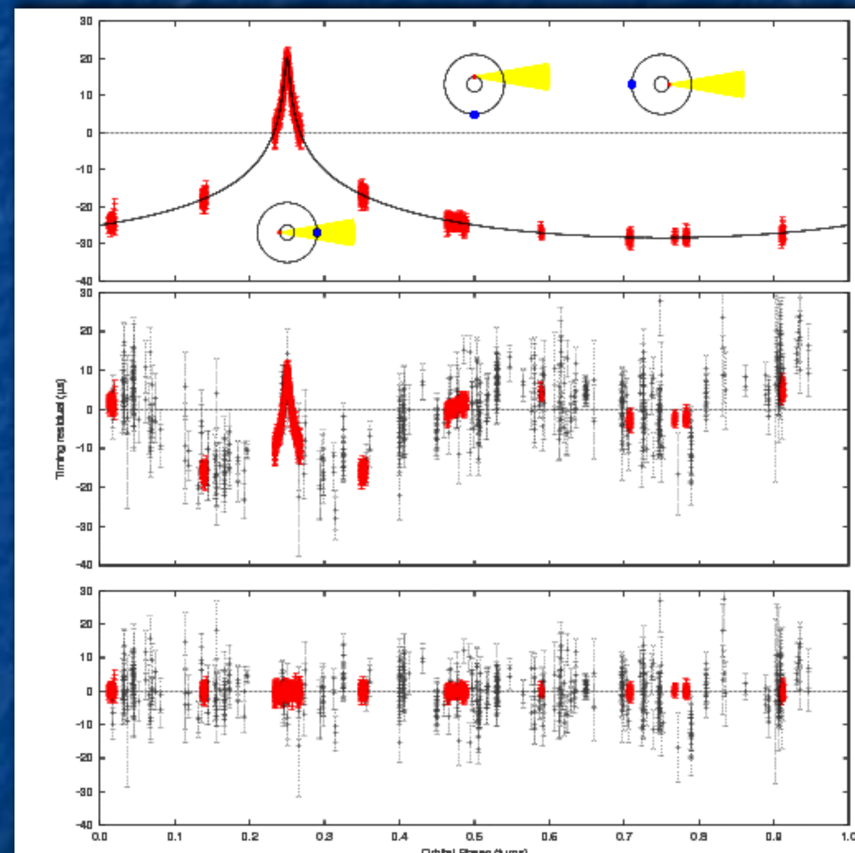
- Very tightly clustered $M=1.35 \pm 0.1\ M_{sun}$
- Does this indicate a very low upper limit on masses?
- Or are formation conditions just similar?



http://www.lsw.uni-heidelberg.de/users/mcamenzi/NS_Mass.jpg

~2 M_{sun} Neutron Stars

- J1614−2230, 1.908+−0.016
  Demorest et al. 2010
- J0348+0432, 2.01+−0.04 M_{sun}
  Antoniadis et al. 2013
- J0740+6620, 2.08+−0.07
  Cromartie et al. 2019
  Fonseca et al. 2021
- Eliminate EOS that are too soft, i.e., whose pressure is too low at the relevant densities



Demorest et al. 2010

No Lutz-Kelker Bias

- People are saying...that NS masses measured using Shapiro delay could be biased high because delay can’t be <0.
- But this is incorrect, in theory and practice
- Theory: claim is equivalent to saying you can’t sample distributions with boundaries
- Practice: latest vs. previous NANOGrav Shapiro estimates, 5/9 *increased* mass

Moment of Inertia?

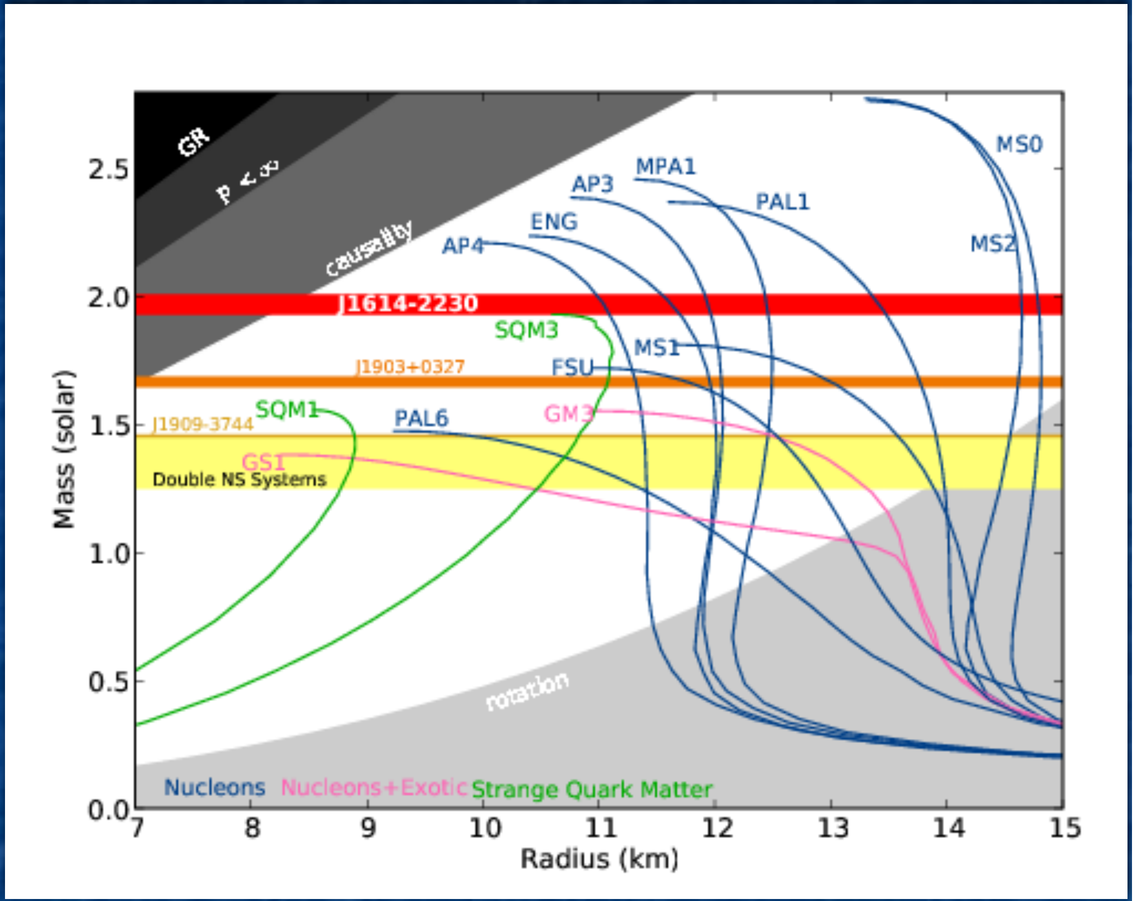
- The double pulsar PSR J0737 has highly precise measurements
- Maybe see extra precession due to frame-dragging? Depends on moment of inertia
- Long hoped, but many complications
  E.g., dP_b/dt has spindown contribution!
- Currently $I_A < 3 \times 10^{45}$ g cm^2 (90%), R<22 km
- Estimate: 11% precision on I_A by 2030

Why Can't We Do Better?

- Huanchen Hu et al., 2020
- Expected frame-dragging contribution to precession: ~4×10^{-4} deg yr^{-1}
- Current precision ~10^{-5} deg yr^{-1}
- But 1PN contribution is 16.9 deg yr^{-1}; thus need to know masses to ~10^{-5} to be sure of frame-dragging contribution; ~2030?
- Hu+ think GW (especially) will take over by then, but I think MOI is still important

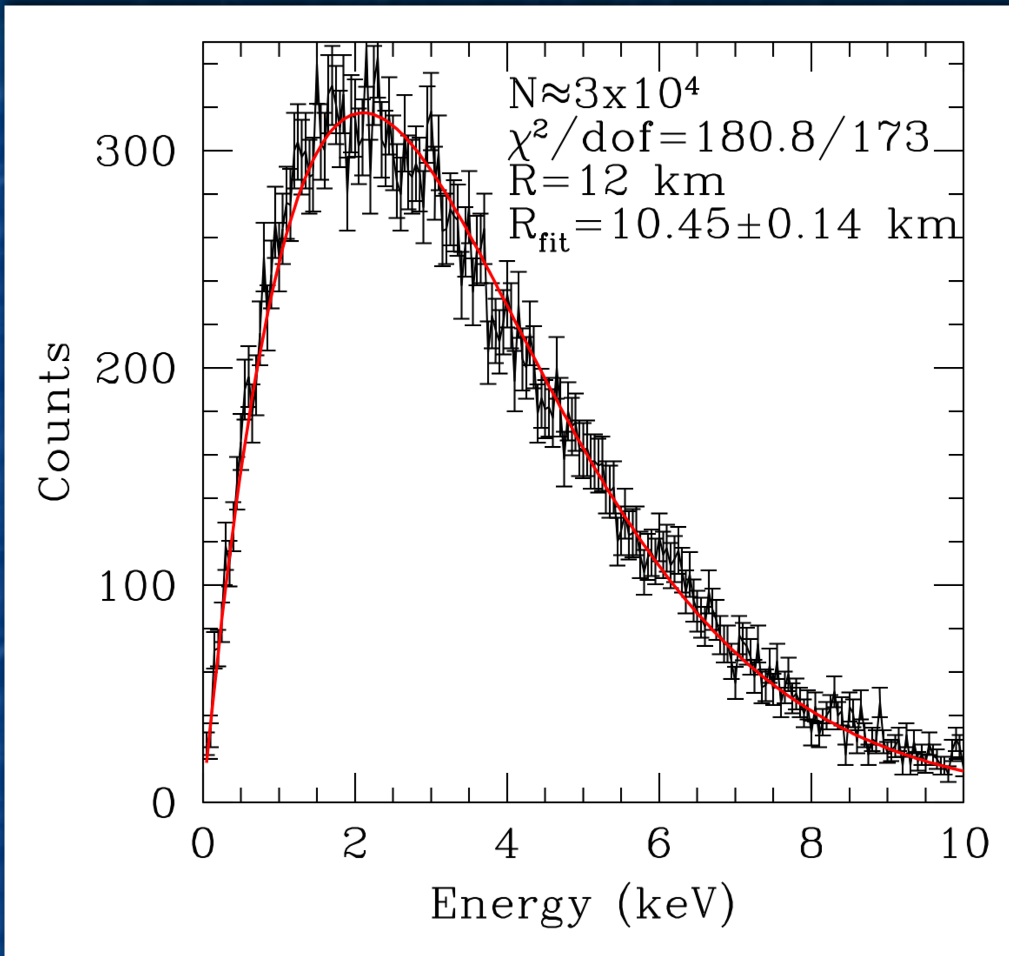
The Importance of Radii

- Radius would provide great EOS leverage
  Wide range in models
- But tough to measure
- Measurements that use just flux and spectra are susceptible to huge systematic error
  One reason: NS atm are fully ionized
- NICER X-ray pulse modeling can help



Demorest+ 2010

Radius Bias with T Variation



Perfect energy response, zero N_H

T varies smoothly from 2 keV (equat) to 0.2 keV (pole).

Fit is good, but R is 13%, and 10σ, low.

Good fit and lack of pulsations does ***not*** guarantee uniformity!

Nättilä+ 2017: free fraction, 12.4+−0.4 km

NICER Reduces Systematic Errors

- Extensive work by Fred Lamb (Illinois) and myself with our collaborators suggests that when we fit *rotational-phase dependent* spectra, such as with NICER, systematic errors are minimized
- We have generated synthetic data using models with different beaming, spectra, spot shapes, temperature distributions etc. than used in fitting the data
- Conclusion: if good fit, no significant bias
  Ongoing in-depth analysis: Isiah Holt, UMd

The NICER Idea in Brief

Bayesian fits: trace rays from hot spots on NS surface, compare with energy-dep waveform

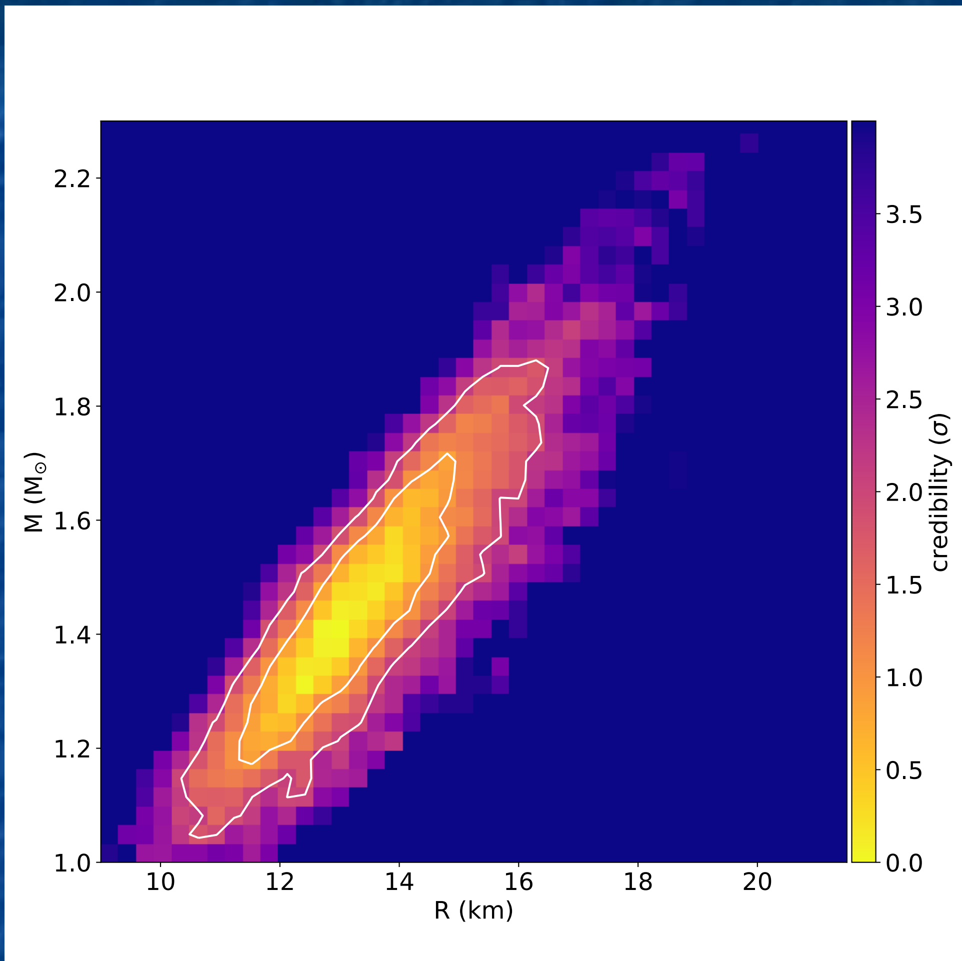
Will feature our results, but also please look at Riley+ 2019, 2021

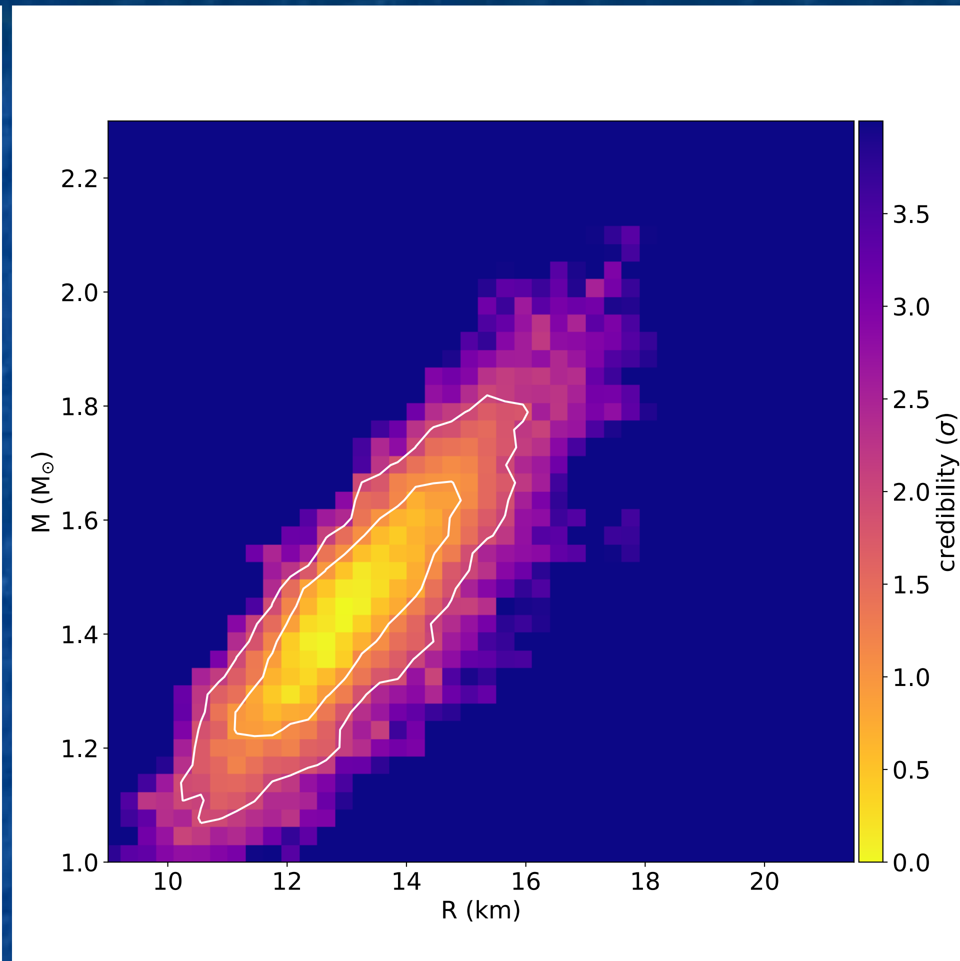
Our Main Results

- For the 205.53 Hz pulsar PSR J0030+0451
  Isolated pulsar: no indep knowledge of M
  We get R_e=13.02(+1.24,−1.06) km and
  M=1.44(+0.15, −0.14) M_{sun} (all 1σ)
- For the 346.53 Hz pulsar PSR J0740+6620
  Mass (from radio) = 2.08+−0.07 M_{sun}
  Radius (our analysis) = 12.2 − 16.3 km

Philosophy: when we fit the X-ray data we allow the radius to be whatever value fits the data. Only when we consider EOS implications do we impose constraints on radius.

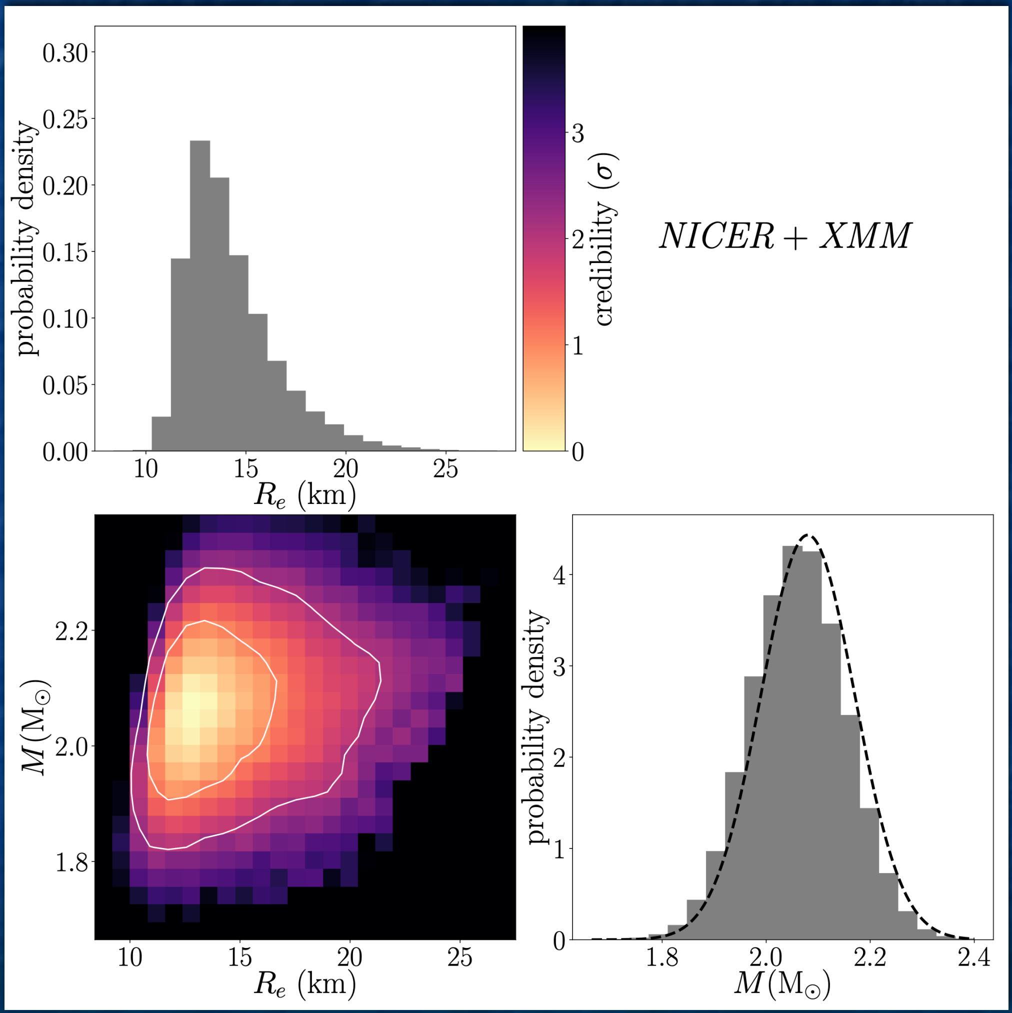
Mass-Radius Posteriors for J0030





Left: M-R posterior for NICER J0030 data, two ovals
Right: M-R posterior for NICER J0030 data, three ovals

J0740 NICER+XMM: M and R

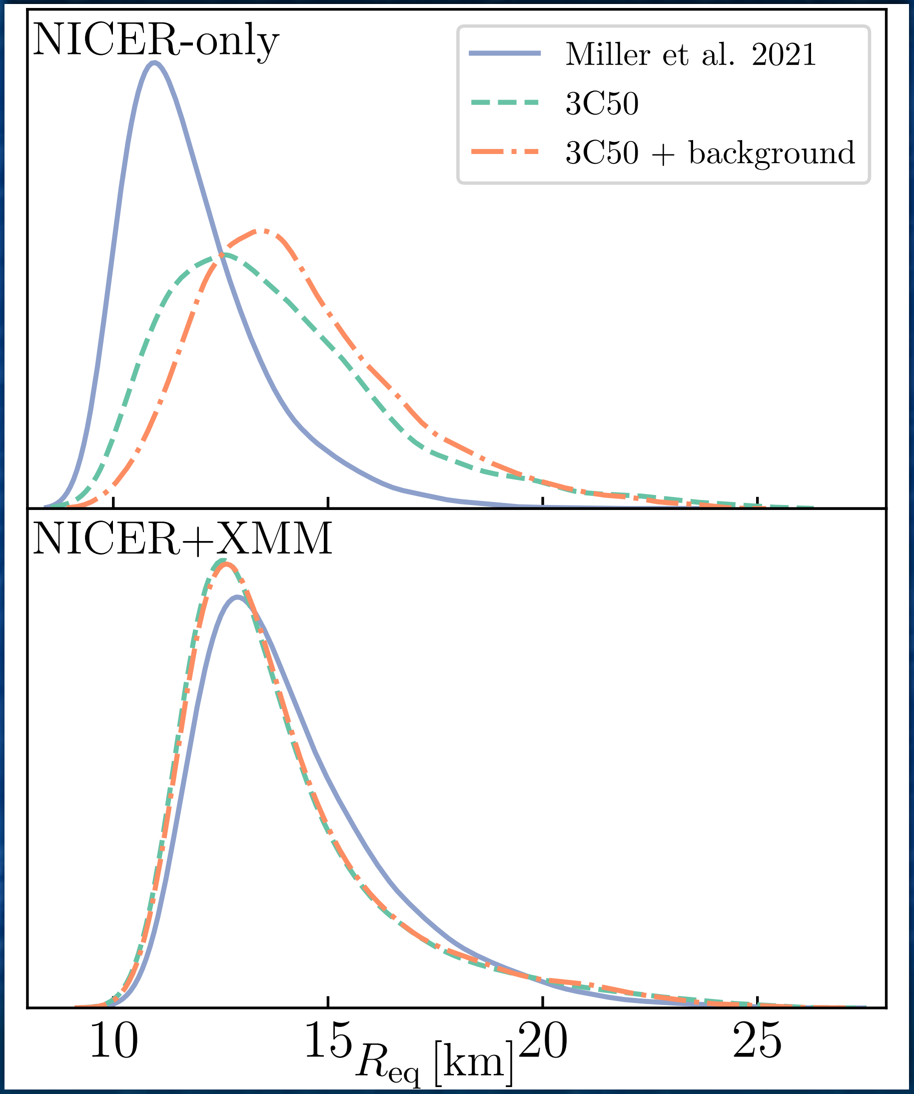


Radius of PSR J0740+6620: $13.7^{+2.6}_{-1.5}$ km (1σ)

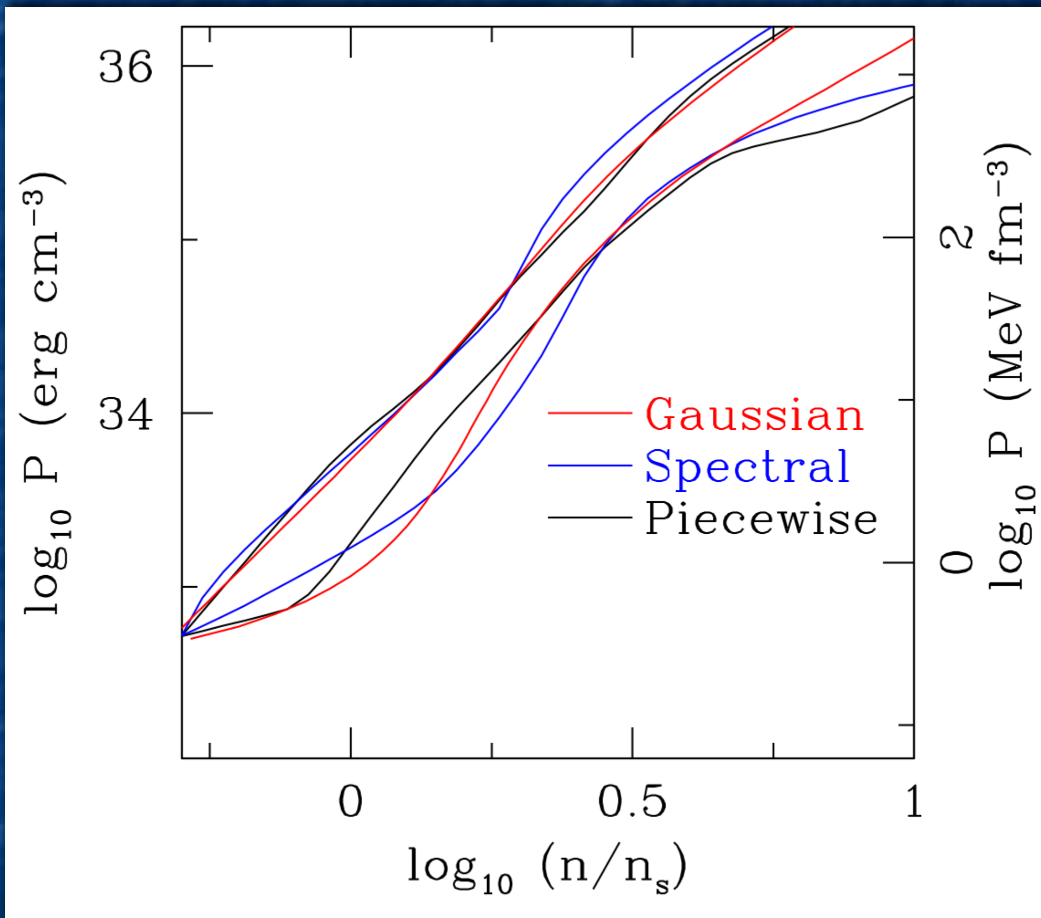
Dashed line: prior on mass from NANOGrav and CHIME/Pulsar data

J0740, with and w/o background

- Both groups have now included NICER background (Salmi+ 22)
- Ron Remillard's "3C50" data set (to late 2021, but with much stricter cuts, so similar total exposure)
- Some updates, but no major EOS implications with these data



J0030, J0740, Other Measurements Provide Tight EOS Constraints

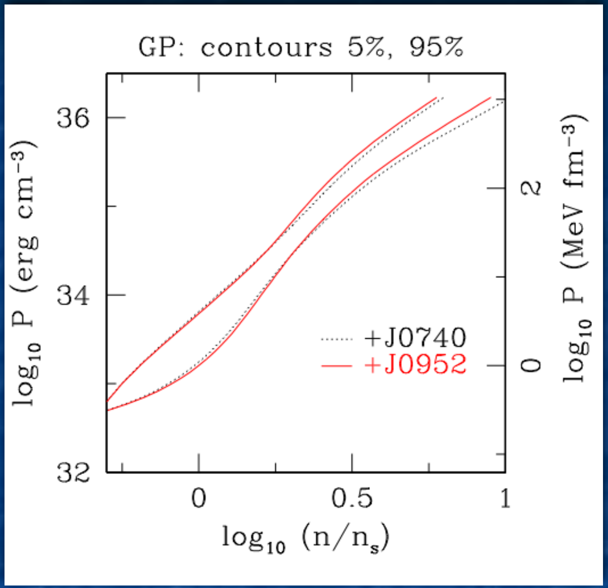


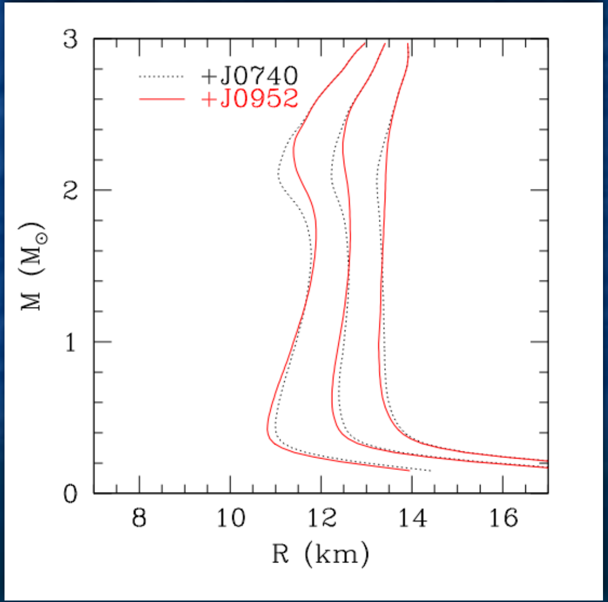
3 EOS models:
- Gaussian process
- Spectral parameterization
- Piecewise polytrope

Good EOS convergence in ~ 1.5 – 5 ρ_{sat} range

Additional high masses?

- What if we get additional high masses?
- Example: PSR J0952, mass 2.35+-0.17 M_{sun} (Romani et al. 2022)
- Increases pressure >$2n_s$
- Reliability is unclear, but precise, reliable masses will continue to help





Conclusions and Prospects

- For densities up to ~5 ρ_{sat}, we are now driven by data rather than by prior assumptions
- NICER will report on additional pulsars and improve current measurements with new data
- In coming years, we hope for additional, and more precise, GW tidal deformabilities (Read talk)
- Some possibility of a measurement of the moment of inertia of one pulsar
- It's a good time to work on dense matter!